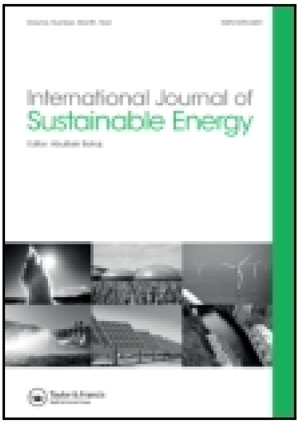

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Global thrust on fuel cells and their sustainability - an assessment of research trends by bibliometric analysis

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Global thrust on fuel cells and their sustainability – an assessment of research trends by bibliometric analysis

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We presented a bibliometric analysis of publications on global scientific and technological research in the field of fuel cell based on the data from Science Citation Index Expanded, Web of Science from 1992 to 2011, to provide insights into the characteristics, research activities and technological breakthrough and identify patterns and tendencies. Articles were assessed by many aspects, including model regression fitting the trend of publication outputs, distribution of words in source title, author keyword and KeyWords Plus. By synthetically analysing the keywords, it can be inferred that application of fuel cell ranges from automobiles to consumer electronic devices. Research especially related to 'proton exchange membrane fuel cell', 'direct methanol fuel cell', 'molten carbonate fuel cell', 'solid oxide fuel cell' and 'catalysts' is the orientation of the fuel cell research in the twenty-first century.

Keywords: fuel cell research; bibliometric analysis; platinum catalysts; SCI-Expanded

1. Introduction

The era of cheap oil is almost over (Jefferson 2006) and countries are looking for alternative and appropriate energy sources to meet their increasing energy demands (Watt and Outhred 2001; del Río, Hernandez, and Gual 2005; Uddin, Taplin, and Yu 2006; Clift 2007). With the realisation of the need for low-carbon technologies (Dunn 2002; Cormio et al. 2003; UNDP 2004), the options for clean and dependable energy sources are limited. Solar energy proves to be one such renewable energy source (Green 2000), but the seasonal variation of solar insolation and the day–night cycle necessitates its storage in a form of useful for versatile applications. Fuel cells, the electrochemical cells converting chemical energy to electrical energy by electrochemical reactions, are increasingly felt as the viable option for a clean and green energy. Coupled with the solar energy harnessing, the fuel cells (regenerative fuel cells) provide themselves as the best solution to the energy needs of the human race (Momirlan and Veziroglu 2002). As the product of the reaction in fuel cell is water, it can well be the future energy source without affecting the environment (Midilli et al. 2005). The fuel cells have been successfully used in space applications and hence their use in terrestrial utilisation requires only tuning and miniaturisation to meet the service conditions at an affordable cost. Invented in 1839 by William Robert Grove (Grove, 1839, 1842) and discovered independently

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at about the same time by a Swiss scientist, Christian F. Shoenbein (Bossel 2000), the fuel cells did not find a place in market till recently though the oil crisis in 1970s rekindled the research on fuel cells. However, the growth rate of fuel cells has increased since then (Schaeffer and Uyterlinde 1998). Fuel cells are gaining momentum now than never before (Stone and Morrison 2002) due to the delivery of high-grade energy, high power density, noiseless operation and harmless reaction product in addition to the eco friendliness. As each country is vying with one another to lead in this field, pooling of the research contributions by the world countries will enable the potential researchers in this field to channelise their efforts towards major breakthroughs. The number of fuel cell-related publications and patents is dramatically increasing (www.fuelcelltoday.com) showing the interest and involvement of the scientists and engineers alike.

In 1996, the term 'bibliometric' was first coined by Fairthorne (1969) and Pritchard (1969). Bibliometric analysis is the application of mathematics and statistical methods to books and other communication media. Bibliometric indicators, for instance, number of publications (Frohlich and Resler 2001), citations (Borić 2008) and journal impact factors (IFs) (Lehrl, 1999) are used for research evaluations. In recent years, five bibliometric indicators such as total, independent, collaboration, first author and corresponding author publications are being used (Wang, Yu, and Ho 2010). Indicators related to citations namely the citations per publication (Moed et al. 1985; Chiu and Ho 2005) and *h*-index (Hirsch 2005) are the most frequently used for the evaluation of publication performances. Furthermore, research trends can also be obtained by word cluster analysis with the results of distribution of the words in paper title, abstract, author keywords and KeyWords Plus in different periods (Mao, Wang, and Ho 2010; Zhang, Xie, and Ho 2010).

In this article, we have attempted to quantify the major players in the field of fuel cell. A bibliometric method based on the analysis of language, journal, Web of Science category, country and institution of the article was used. Distributions of words in article title, author keywords and KeyWords Plus in different periods were also analysed.

2. Methodology

Data were obtained from the online version of Science Citation Index Expanded (SCI-Expanded) databases of the Web of Science from Thomson Reuters. According to *Journal Citation Reports* (*JCR*) of 2011, it indexes 8336 journals with citation references across 176 Web of Science categories in science edition. 'Fuel cell' and 'fuel cells' were used to search the database from 1992 to 2011. The searched document information included authors, contact address, title and year of publication, keywords, Web of Science categories and journals. The records were downloaded into Microsoft Excel software, additional coding was manually performed for the number of authors and country of origin of the collaborators. Articles from Hong Kong were not included in China. Articles originating from England, Scotland, Northern Ireland and Wales were grouped under the UK heading. Besides, the reported IF of each journal was obtained from the 2011 *JCR*. Contributions of different institutions and countries were estimated by the location of the affiliation of at least one author of the published articles. Collaboration type was determined by the addresses of the authors and the term 'single country article' was assigned if the addresses of the researchers were of the same country. The term 'internationally collaborative article' was designated to those articles that were co-authored by researchers from multiple countries. The term 'single institution article' was assigned, if the researchers' addresses were of the same institution. The term 'inter-institutionally collaborative article' was assigned, if authors were from different institutions (Li and Ho 2008). All numerical analyses used integer counts, that is, if an article was authored by persons from two different institutions/countries, each country was counted once. As a result, the percentages may add up to values greater than 100.

3. Results and discussion

3.1. *Document types and languages*

There are 40,231 publications with 16 document types indexed, which includes 31,566 research articles. Article, as the most popular document type, composes 78% of the total publications and is followed distantly by research papers in proceedings (5129; 13%), reviews (1225; 3.0%), meeting abstracts (915; 2.3%), news items (672; 1.7%), editorial materials (353; 0.88%), letters (166; 0.41%), corrections (100; 0.25%), notes (42; 0.10%), book chapter reviews (34), reprints (9), addition corrections (7), book chapter articles (5), biographical-item (4), book reviews (3) and item about an individual (1). This reveals the journal article as the preferred mode of result dissemination. As journal articles represented the peer-reviewed document types, only the 31,566 original articles were used for further analysis. The emphasis of the following discussion is to determine the pattern of scientific production, research activity trends of authors, institutions, countries and the trends in the research subject addressed. Articles in English hold a very high share (96%), whereas local publications in Chinese (2.0%) and Japanese (0.78%) follow with a meagre share. Very few publications have been reported in other languages. This reveals the tendency of the fuel cell researchers to reach out to a wider audience. This also facilitated better dissemination of knowledge and developments in this field worldwide.

3.2. *Publication characteristics*

Numbers of SCI-Expanded journal articles including ‘fuel cell’ or ‘fuel cells’ in title only during the last 100 years were counted. Figure 1 shows the number of research articles based on searching from titles on fuel cells. It could be observed that the oil crisis in the 1970s had kindled research on fuel cell which had remained almost dormant till then. As the cost of fuel cells could not compete with that of the other energy sources available then, the research did not dramatically increase and hence during 1955–1990, the research on fuel cells was rather slow. It started showing increased activities after 1990 due to the compelling need to look for the alternative energy sources to meet the increasing energy demands. Research emphasis was also witnessed in the development of improved materials for fuel cell (Etsell and Flengas 1971; Janssen and Moolhuysen 1976a). The steep increase in research on fuel cells in the new century is due to the cumulative effect of many factors such as the need to prepare for post-oil period, concern for the environment, the need to contain the environmental damage caused already, growing populations and the high energy demand. It can be summed up that along with the development of SCI-Expanded, fuel cell research that continually grew in this long period, started to go up significantly in the year of 1991 and rocketed in the twenty-first century. Built on many breakthroughs during 1992–2011, especially in the recent decade, fuel cell research has become one of the most important and dynamic fields of human research (Lao, Wen, and Ren 2002; Wang et al. 2002; Hickner et al. 2004). As many evidences point towards a permanent oil crisis, the research and development in alternative energy sources and their technologies become very significant. While the energy source diversification has been suggested as a solution to the energy crisis (Bolivar, Mostany, and Garcia 2006), the magnificent role of fuel cell technology is immensely felt now than ever before. Technology forecasting of hydrogen energy and fuel cell as the new clean energy is also reported (Chen, Chen, and Lee 2010). This is also revealed by the steady increase in the documents other than research articles written with the aim of awareness creation and popularisation of fuel cells among end users. Reviews on the individual components of fuel cell such as gas diffusion layer (Cindrella et al. 2009) and catalysts (Janssen and Moolhuysen 1976b) reveal the research emphasis on the improvement in the efficiency of fuel cells. Table 1 summarises the characteristics of the fuel cell scientific articles such as total number of articles (A), authors (AU), average number of

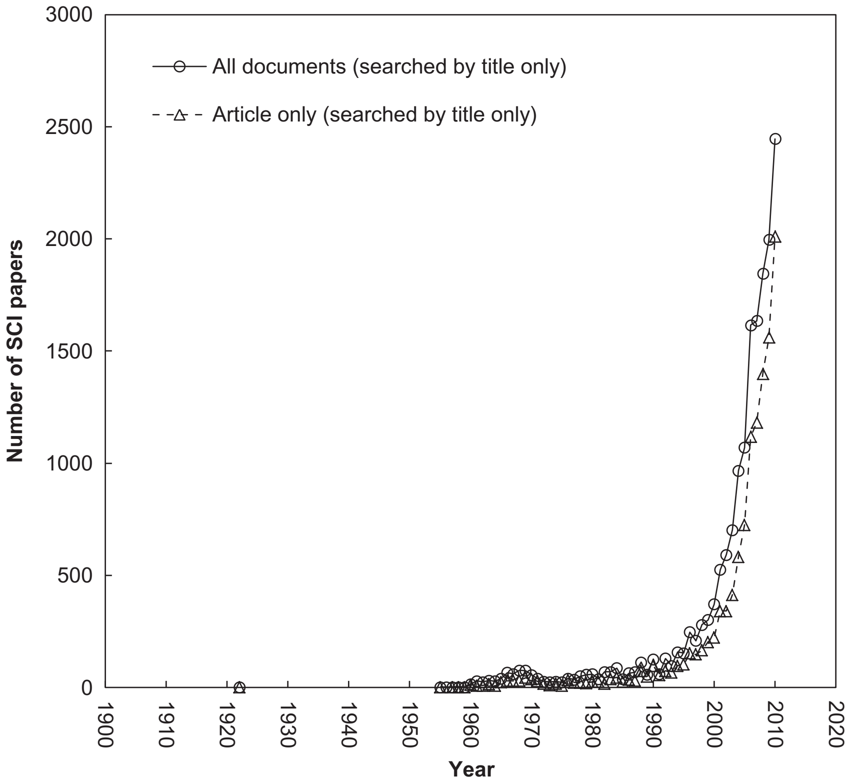

Figure 1. World SCI-Expanded publications on fuel cell since 1900 (searched by title only).

authors per article (AU/A), cited reference count (NR), average cited reference count per article (NR/A), page count (PG) and average page count per article (PG/A). A tremendous increase in the number of authors involved in fuel cell research is observed in the last few years. Though renewed interest in the fuel cell research started in the 1970s, intense research activity is witnessed in the last decade only. A similar trend has also been observed in the analysis of the growth curve of the fuel cells during 1970–2005 (Kajikawa et al. 2008). For a period of 35 years of analysis, the average year, that is, the point of time of equal number of publications before and after has been reported as 2002. This implies a steep rise in publication after 2002.

3.3. *Article in web of science categories and journals*

Based on the classification of categories in *JCR* in 2011, the article output data of fuel cell research were distributed over 113 Web of Science categories. The top 20 productive categories were statistically analysed in Table 2. As fuel cell research is an interdisciplinary subject involving many branches of science and technology, an analysis of the articles under various categories has been presented in Table 2. The total number of articles published (TA) in the last 20 years in the various categories, number of journals in those categories (NJ) and articles per journal in each category (TA/NJ) have been considered for this analysis. The basic reaction mechanism of any fuel cell is electrochemical and hence the category of electrochemistry registers the highest number of articles. Thorough analysis of TA in Table 2 reveals a significant contribution in fields ranging from electrochemistry to mechanical engineering. Figure 2 compares the growth trends of seven categories of fuel cell research with more than 2000 articles. Though the categories of

Table 1. Characteristics of fuel cell scientific articles from 1992 to 2011.

Year	TA	AU	AU/TA	NR	NR/TA	PG	PG/TA
1992	145	487	3.4	2797	19	1192	8.2
1993	147	440	3.0	2837	19	1213	8.3
1994	187	558	3.0	3047	16	1420	7.6
1995	217	756	3.5	4311	20	1833	8.4
1996	312	1022	3.3	6253	20	2672	8.6
1997	293	1005	3.4	5713	19	2263	7.7
1998	359	1185	3.3	6931	19	2827	7.9
1999	410	1452	3.5	8390	20	3128	7.6
2000	480	1706	3.6	10,670	22	3753	7.8
2001	617	2059	3.3	13,746	22	4944	8.0
2002	737	2724	3.7	16,156	22	5470	7.4
2003	974	3719	3.8	22,838	23	7784	8.0
2004	1474	5709	3.9	36,507	25	11,588	7.9
2005	1775	6887	3.9	46,578	26	14,156	8.0
2006	2588	10,583	4.1	69,531	27	20,645	8.0
2007	2982	12,183	4.1	83,395	28	23,539	7.9
2008	3505	14,844	4.2	104,187	30	27,747	7.9
2009	3985	16,996	4.3	122,210	31	30,471	7.6
2010	4836	21,356	4.4	161,964	33	38,589	8.0
2011	5543	24,846	4.5	191,050	34	44,167	8.0
Total	31,566			919,111		249,401	
Average		4.1		29.1		7.9	

Note: TA: number of articles; AU: number of authors; AU/TA: the average number of authors per article; NR: cited reference count; NR/TA: the average cited reference count per article; PG: page count; PG/TA: the average page count per article.

Table 2. Web of Science category of article on fuel cell.

Web of Science category	TA (%)	NJ	TA/NJ
Electrochemistry	13,973 (44)	17	822
Energy and fuels	9413 (30)	62	152
Physical chemistry	7841 (25)	96	82
Multidisciplinary materials science	4568 (14)	122	37
Chemical engineering	3003 (10)	62	48
Multidisciplinary chemistry	2249 (7.1)	135	17
Coatings and films materials science	2222 (7.0)	7	317
Polymer science	1830 (5.8)	43	43
Condensed matter physics	1769 (5.6)	16	111
Nanoscience and nanotechnology	1406 (4.5)	5	281
Applied physics	1096 (3.5)	21	52
Environmental sciences	904 (2.9)	139	7
Ceramics materials science	852 (2.7)	24	36
Electrical and electronic engineering	807 (2.6)	160	5
Metallurgy and metallurgical engineering	762 (2.4)	40	19
Analytical chemistry	693 (2.2)	52	13
Environmental engineering	687 (2.2)	27	25
Biotechnology and applied microbiology	588 (1.9)	118	5
Thermodynamics	579 (1.8)	3	193
Mechanical engineering	558 (1.8)	80	7

Note: TA: total published articles in the 20 years; NJ: number of journals in a category; TA/NJ: articles per journal in each category.

physical chemistry, energy and fuels showed a similar trend, the higher number of articles in the latter came to be felt from 2005 onwards indicating the accommodation of fuel cell in a wider area. The increasing number of fuel cell articles in journals related to environmental sciences foresees fuel cells as the universal panacea for the environmental problems.

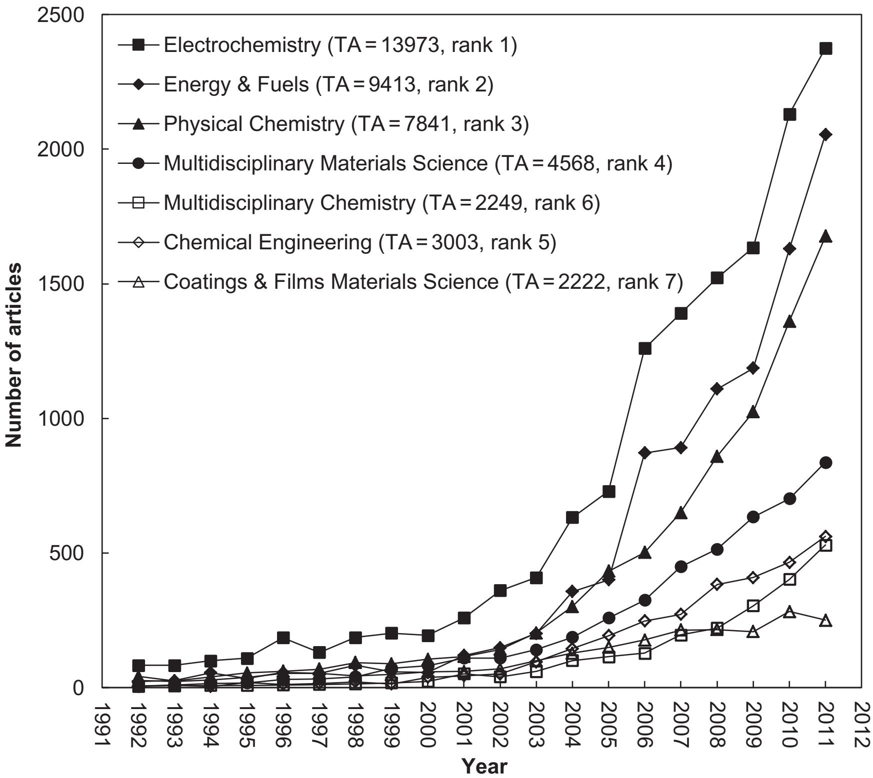

Figure 2. Comparison of the growth trends of top 7 Web of Science categories fuel cell-related articles during the last 20 years.

In total, 31,566 articles were published in 1313 journals, including not only specialty journals, but also journals of other disciplines. Twenty journal-wise articles of fuel cell documents are presented in Table 3. As some of the journals could be accommodated under more than one category, there is a possibility of counting of an article in common categories in all related fields. The leading journal of fuel cell research, *Journal of Power Sources*, published the most number of articles with 4708 articles thereby comprising 15% of the total articles, followed by *International Journal of Hydrogen Energy* (2125), *Journal of the Electrochemical Society* (1997) and *Electrochimica Acta* (1126). Contrastingly, as regards to the IF, the rank of journals changed. *Chemical Reviews* won the first place with the highest IF (40.197) with only one article. In addition, *Nature* (IF = 36.280) ranked second with 21 articles, *Nature Materials* (IF = 32.841) ranked third with 23 articles and *Science* (IF = 31.201) ranked fourth with 38 articles.

3.4. *Publication of countries and institutions*

The contribution by different countries was determined by the location of the institution of the authors of the published papers. There were 294 articles without any author address information on the Web of Science. Of all the 31,272 articles with the address of authors, 26,340 (84%) were single country articles and 4932 (16%) were international collaborative articles. Table 4 lists the top 30 countries ranked by total number of articles (TA). Ranks of single country articles, international collaborative articles, first author articles, corresponding author articles and their percentages are also shown in Table 4. The USA ranks first in single country authorship followed

Table 3. Journal-wise articles on fuel cells.

Source	TA (%)	IF	Web of Science category (position)
Journal of Power Sources	4708 (15)	4.951	Electrochemistry (2/27); energy and fuels (9/81)
International Journal of Hydrogen Energy	2125 (6.7)	4.054	Chemistry physical (29/134); electrochemistry (5/27); energy & fuels (12/81)
Journal of the Electrochemical Society	1997 (6.3)	2.590	Electrochemistry (13/27); coatings and films materials science (1/18)
Electrochimica Acta	1126 (3.6)	3.832	Electrochemistry (7/27)
Solid State Ionics	879 (2.8)	2.646	Chemistry physical (50/134); condensed matter physics (17/69)
Journal of Membrane Science	685 (2.2)	3.850	Chemical engineering (8/133); polymer science (11/78)
Electrochemistry Communications	640 (2.0)	4.859	Electrochemistry (3/27)
Journal of Physical Chemistry C	547 (1.7)	4.805	Physical chemistry (26/134); multidisciplinary materials science (23/231); nanoscience and nanotechnology (17/66)
Fuel Cells	470 (1.5)	3.149	Electrochemistry (10/27); energy & fuels (20/81)
Electrochemical and Solid State Letters	444 (1.4)	1.995	Electrochemistry (15/27); multidisciplinary materials science (62/231)
Journal of Fuel Cell Science and Technology	434 (1.4)	1.136	Electrochemistry (21/27); energy and fuels (45/81)
Journal of Applied Electrochemistry	349 (1.1)	1.745	Electrochemistry (17/27)
Journal of Materials Chemistry	348 (1.1)	5.968	Physical chemistry (18/134); multidisciplinary materials science (17/231)
Journal of Physical Chemistry B	347 (1.1)	3.696	Physical chemistry (32/134)
Journal of Electroanalytical Chemistry	329 (1.0)	2.905	Analytical chemistry (21/73); electrochemistry (11/27)
Applied Catalysis A-General	307 (1.0)	3.903	Physical chemistry (31/134); environmental sciences (20/205)
Journal of Alloys and Compounds	293 (0.93)	2.289	Physical chemistry (58/134); multidisciplinary materials science (50/231); metallurgy and metallurgical engineering (4/75)
Chemistry of Materials	281 (0.89)	7.286	Physical chemistry (14/134); multidisciplinary materials science (13/231)
Applied Catalysis B-Environmental	248 (0.79)	5.625	Physical chemistry (20/134); engineering chemical (6/133); environmental engineering (2/45)
Electrochemistry	245 (0.78)	0.954	Electrochemistry (22/27)

Note: TA: total published articles in the 20 years.

by China, Japan, South Korea and Canada. In international collaboration also, the USA tops the list followed by China, Germany, Japan and France. The reprint author articles follow the same trend as that of the single country authorship and first authorship, revealing the prominence of the USA in fuel cell research. The seven major industrial countries (G7: Canada, France, Germany, Italy, Japan, the UK and the USA) are ranked in the top 11 in single country articles with 55% contribution. Three Asian countries, China, South Korea and Taiwan, have also been ranked in top positions. Comparison of the growth trends of articles by the top eight major productive countries during the study period is shown in Figure 3. The rate of publications by China since 2000 reveals a marked increase, in commensurate with that of the USA. The slope of the curve since 2005, promises China to play a major role in this area as also reported by Arunachalam and Viswanathan (2008). The current trend on fuel cell research in China could be attributed to the huge financial impetus and the following facts (Feller 2004):

1. Public and private investment in fuel cell development in China over the next few years has been projected to be over (US) $500 million.

Table 4. Single country, international collaboration, first author and reprint author articles of the world countries on fuel cells.

Country	TA	TA R (%)	SA R (%)	CA R (%)	FA R (%)	RA R (%)	C%
USA	7417	1 (24)	1 (22)	1 (33)	1 (21)	1 (21)	22
China	5642	2 (18)	2 (16)	2 (28)	2 (16)	2 (16)	24
Japan	3676	3 (12)	3 (12)	4 (12)	3 (11)	3 (11)	16
South Korea	2307	4 (7.4)	4 (7.0)	8 (9.4)	4 (6.6)	4 (6.7)	20
Germany	1860	5 (5.9)	6 (4.4)	3 (14)	6 (4.5)	6 (4.7)	38
Canada	1717	6 (5.5)	5 (4.7)	7 (10)	5 (4.7)	5 (4.7)	27
UK	1332	7 (4.3)	8 (3.2)	6 (10)	8 (3.3)	8 (3.5)	37
France	1262	8 (4.0)	11 (2.7)	5 (11)	9 (2.9)	9 (3.2)	45
Taiwan	1245	9 (4.0)	7 (4.0)	14 (3.8)	7 (3.7)	7 (3.7)	15
Italy	1080	10 (3.5)	10 (2.7)	9 (7.3)	10 (2.9)	11 (2.8)	33
India	1024	11 (3.3)	9 (3.1)	13 (4.3)	11 (2.8)	10 (2.9)	21
Spain	875	12 (2.8)	12 (2.1)	10 (6.6)	12 (2.3)	12 (2.2)	37
Brazil	505	13 (1.6)	13 (1.5)	20 (2.5)	13 (1.4)	13 (1.4)	24
Russia	490	14 (1.6)	14 (1.2)	17 (3.4)	14 (1.2)	14 (1.3)	34
Singapore	489	15 (1.6)	15 (1.0)	12 (4.4)	15 (1.2)	15 (1.2)	44
Australia	427	16 (1.4)	23 (0.59)	11 (5.5)	20 (0.82)	17 (0.95)	64
Switzerland	425	17 (1.4)	16 (1.0)	16 (3.5)	16 (1.1)	16 (1.0)	41
Sweden	392	18 (1.3)	19 (0.77)	15 (3.8)	17 (1.0)	18 (0.93)	48
Denmark	346	19 (1.1)	18 (0.84)	19 (2.6)	18 (0.90)	19 (0.87)	36
The Netherlands	324	20 (1.0)	21 (0.74)	18 (2.6)	21 (0.80)	21 (0.80)	40
Iran	293	21 (0.94)	17 (0.93)	32 (1.0)	19 (0.90)	20 (0.84)	17
Turkey	278	22 (0.89)	20 (0.75)	26 (1.6)	22 (0.76)	22 (0.77)	29
Hong Kong	247	23 (0.79)	22 (0.68)	27 (1.4)	23 (0.62)	23 (0.68)	28
Greece	241	24 (0.77)	25 (0.57)	23 (1.9)	23 (0.62)	24 (0.63)	38
Poland	238	25 (0.76)	24 (0.58)	25 (1.7)	25 (0.59)	25 (0.58)	35
Thailand	217	26 (0.69)	27 (0.45)	22 (2.0)	26 (0.57)	26 (0.50)	45
Portugal	198	27 (0.63)	30 (0.33)	21 (2.3)	28 (0.51)	28 (0.48)	57
Mexico	185	28 (0.59)	26 (0.50)	30 (1.1)	27 (0.52)	27 (0.50)	29
Norway	161	29 (0.51)	28 (0.36)	29 (1.3)	29 (0.39)	30 (0.40)	41
Finland	158	30 (0.51)	29 (0.34)	27 (1.4)	30 (0.36)	29 (0.42)	43

Note: TA: total published articles in the 20 years; SA: single country articles; CA: international collaborative articles; FA: first author articles; RA: reprint author articles (corresponding author articles); R (%): ranking of articles (percentage of all articles published).

2. The demand for alternative fuels in China is driven by the Chinese government's desire to reduce air pollution, particularly in urban centres and reduce the country's dependence on imported oil.
3. Transportation is considered to be the most important initial market for fuel cells in China.
4. The commitment of Chinese government in 2002, to invest about $18 million in a three-year proton exchange membrane fuel cell (PEMFC) development programme for the development of 75 kW and 150 kW PEMFC systems.
5. During China's 10th five-year plan (2001–2005), the Chinese Ministry of Science and Technology approved a $165-million R&D programme to develop advanced hybrid-electric drive and fuel cell-vehicles.

Thus, with a clear fuel cell road map, China has been following its fuel cell research activities vigorously.

'BRIC' countries – Brazil, Russia, India and China have the fastest growing economies in the world and it has been predicted that in less than 40 years, the BRIC economies collectively will be larger than the G6 (the USA, Japan, the UK, Germany, France and Italy) (Wilson and Purushothaman 2003). In 1997, when the National Basic Research Program (also called the 973 Program) was approved by the Chinese government (www.973.gov.cn), the number of articles from China was found to increase impressively and from then onwards, the articles from China grew sharply, while those of India, Brazil and Russia increased slowly only after 2001, which might

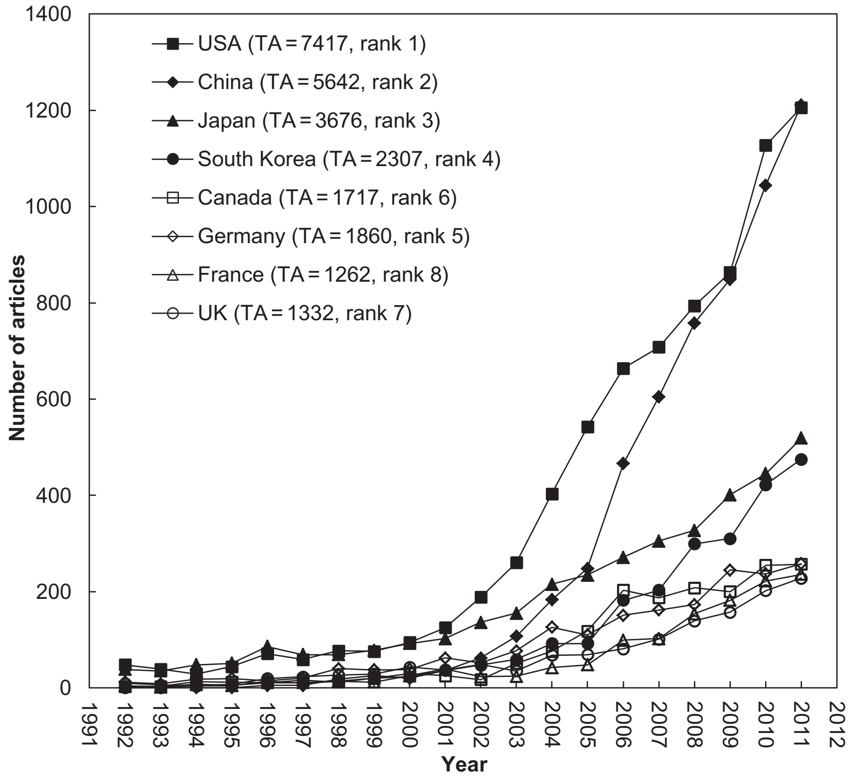

Figure 3. Comparison of the growth trends of top eight major productive countries' articles during the last 20 years.

be the evidence for the remarkable differences in their development of technologies (Figure 4). Research publication of 'Asia four tigers', South Korea, Taiwan, Singapore and Hong Kong is also shown in Figure 5. Articles from South Korea and Taiwan grew sharply, while those of Singapore and Hong Kong increased slowly after 2005. In addition, South Korea published high impact articles, for example, a highly cited article 'ordered nanoporous arrays of carbon supporting high dispersions of platinum nanoparticles' in 2001 (Joo et al. 2001).

The contributions of different institutions were determined by the affiliation of at least one author. Of the 31,272 articles with author addresses, 4973 (16%) were institution independent articles and 26,299 (84%) were inter-institutional collaborations by two or more institutions. There are 16,081 institutions devoted to the fuel cell-related research, of which Chinese Academy of Sciences is the most productive institution followed by the Pennsylvania State University in the USA and the National Institute of Advanced Industrial Science and Technology in Japan. However, a bias appeared because the Chinese Academy of Sciences, the Russian Academy of Sciences and the Indian Institute of Technology have many branches in different cities. At present, the articles of these three institutions were pooled under single heading for each and hence articles divided among their respective branches would result in different rankings. Thus, the most productive institution is the Pennsylvania State University of the USA which has published 414 articles. The Chinese Academy of Sciences published the most first author and corresponding author articles as well as the most independent articles. The top 20 most productive institutions and their respective outputs are presented in Table 5. Among the top 20 institutions, there are five institutions each from China and the USA, followed by three from South Korea, two each from Japan and one institution each from Spain, the UK, Singapore, Canada and Russia. From the results, it could be inferred

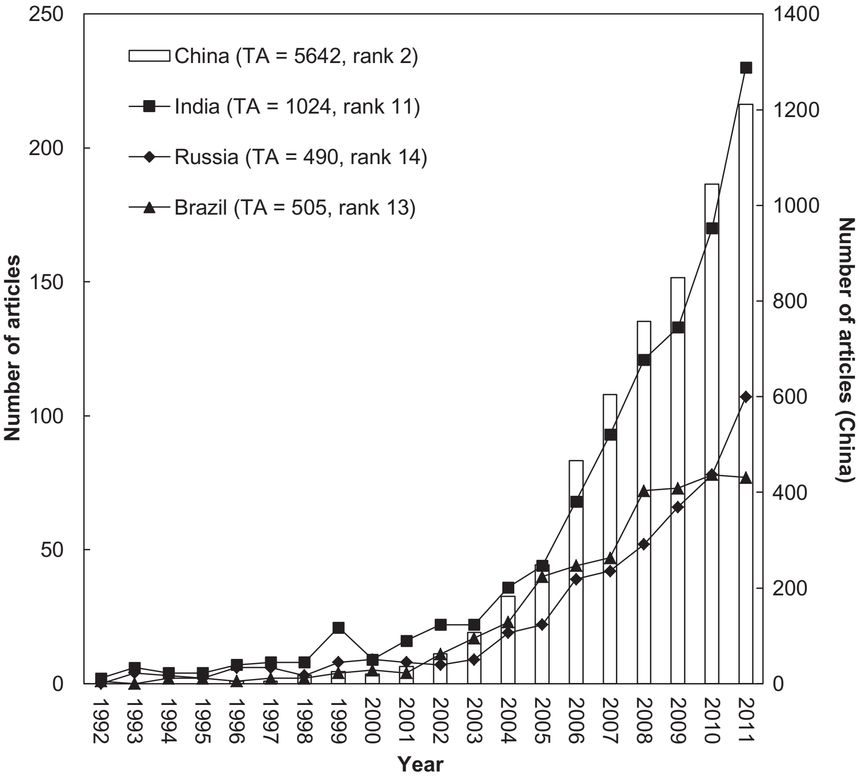

Figure 4. Comparison of the growth trends of BRIC's articles during the last 20 years.

that more institutions are involved in fuel cell research in the USA and China. The increase in the allotment for research on fuel cells by the respective governments and the compelling need for the zero emission regulation demanded by the climate change have accelerated the fuel cell-related research in all countries.

3.5. *Distribution of keywords*

The author keywords supply reasonable details of the subject of the articles. Especially, the analysis of author keywords could offer information on the research trend and concern of the researchers. Bibliometric method of analysis concerning author keywords can be found in recent years (Chiu and Ho 2007; Xie, Zhang, and Ho 2008; Li 2009). The technique of statistical analysis of author keywords might be aimed at discovering directions of scientific research and could prove important for monitoring the development of science and programmes. Furthermore, KeyWords Plus, which supplied additional search terms, was extracted from the titles of papers cited by authors in their bibliographies and footnotes in the Web of Science database (Garfield 1990). The KeyWords Plus analysis as an independent supplement reveals the contents of the articles with more details. Examination of author keywords in this study period revealed that 32,069 author keywords were used, among which 22,968 (72%) keywords appeared only once and 3844 (12%) keywords appeared twice. The large number of author keywords mentioned only once or twice probably shows a lack of continuity in research in this field and a wide disparity in research focuses (Chuang, Huang, and Ho 2007). Furthermore, these keywords might not be the standard or widely accepted by researchers (Ugolini et al. 2001). The ranking of the keywords based on the frequency

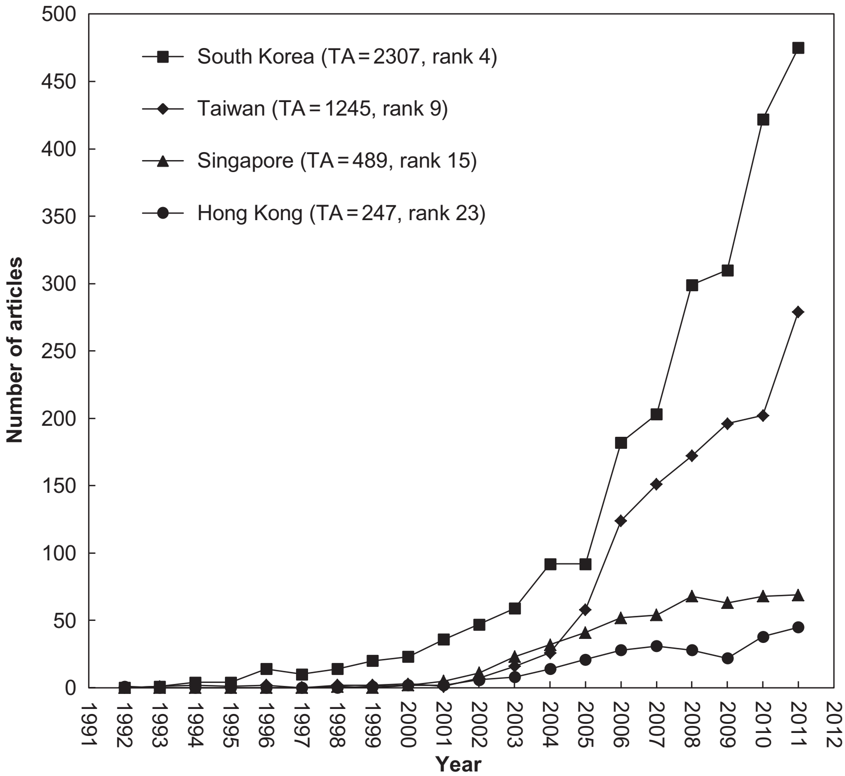

Figure 5. Comparison of the growth trends of Asia tigers' articles during the last 20 years.

of usage has been listed for the period of study and then split over an interval of five years period. The author keywords which appeared in the top 30 positions in the last 20 years are displayed in Table 6. Other than the search keywords, 'fuel cell' and 'fuel cells', the next four keywords most frequently used were 'solid oxide fuel cell (SOFC)', 'hydrogen' and 'direct methanol fuel cell' (DMFC), which show the hot spots in fuel cell research worldwide. Moreover, an increase could be found in the ranking of the keywords 'DMFC', 'PEMFC', 'proton conductivity', 'hydrogen production', 'DMFC' and 'microbial fuel cell (MFC)'. The SOFC, DMFC, PEMFC and PEMFC would be the hot topics in future. Though different parameters are used for the classification of fuel cells, the most commonly employed is the electrolyte used in the fuel cell and hence they are classified as,

1. PEMFC
2. Phosphoric acid fuel cell
3. Alkaline fuel cell
4. Molten carbonate fuel cell (MCFC)
5. SOFC
6. DMFC
7. MFCs

While all fuel cells except DMFC derive their names from the nature of electrolyte used in them along with the commonness of using gaseous reactants, DMFC derives its name from the fuel. It uses the liquid fuel (methanol) directly fed to the anode. In addition to the above classes, the MFC promise as the generator of electricity, hydrogen and chemical products from organic wastes

Table 5. Institution wise contribution of papers on fuel cells.

Institution	TA	TA R (%)	SA R (%)	CA R (%)	FA R (%)	RA R (%)	C%
Chinese Academy of Sciences, China	1,184	1 (3.8)	1 (3.9)	1 (3.8)	1 (2.8)	1 (0.88)	84
Pennsylvania State University, USA	414	2 (1.3)	3 (1.4)	4 (1.3)	2 (1.1)	6 (0.31)	83
National Institute of Advanced Industrial Science and Technology, Japan	403	3 (1.3)	37 (0.44)	2 (1.4)	5 (0.9)	74 (0.13)	95
University of Science and Technology of China, China	383	4 (1.2)	2 (1.7)	6 (1.1)	4 (1.0)	3 (0.39)	78
Harbin Institute of Technology, China	381	5 (1.2)	19 (0.6)	3 (1.3)	3 (1.0)	21 (0.21)	92
Nanyang Technological University, Singapore	318	6 (1.0)	12 (0.8)	8 (1.1)	8 (0.72)	13 (0.23)	87
Pacific Northwest National Laboratory, USA	315	7 (1.0)	73 (0.28)	5 (1.1)	17 (0.59)	196 (0.068)	96
Consejo Superior de Investigaciones Científicas (CSIC), Spain	307	8 (1.0)	50 (0.36)	7 (1.1)	11 (0.67)	40 (0.17)	94
Korea Institute of Science and Technology, South Korea	302	9 (1.0)	15 (0.72)	9 (1.0)	20 (0.58)	7 (0.27)	88
Shanghai Jiao Tong University, China	285	10 (0.91)	18 (0.64)	12 (1.0)	6 (0.74)	29 (0.19)	89
Seoul National University, South Korea	284	11 (0.91)	19 (0.6)	11 (1.0)	13 (0.64)	23 (0.20)	89
University of South Carolina, USA	279	12 (0.89)	10 (0.86)	15 (0.9)	7 (0.73)	22 (0.20)	85
National Research Council Canada, Canada	277	13 (0.89)	39 (0.42)	10 (1.0)	19 (0.58)	37 (0.17)	92
Russian Academy of Science, Russia	272	14 (0.87)	41 (0.40)	13 (1.0)	9 (0.69)	167 (0.074)	93
Jilin University, China	259	15 (0.83)	7 (1.0)	18 (0.8)	22 (0.52)	7 (0.27)	81
Tokyo Institute of Technology, Japan	256	16 (0.82)	142 (0.14)	14 (0.95)	15 (0.61)	398 (0.039)	97
University of London Imperial College of Science, Technology & Medicine, UK	248	17 (0.79)	14 (0.74)	18 (0.80)	16 (0.60)	40 (0.17)	85
Georgia Institute of Technology, USA	247	18 (0.79)	5 (1.0)	21 (0.75)	12 (0.65)	23 (0.20)	79
University of Connecticut, USA	247	18 (0.79)	4 (1.4)	23 (0.68)	9 (0.69)	10 (0.25)	72
Korean University of Science and Technology, South Korea	238	20 (0.76)	16 (0.66)	20 (0.78)	14 (0.63)	17 (0.22)	86

Note: TA: total published articles in the 20 years; SA: single institution articles; CA: inter-institutionally collaborative articles; FA: first author articles; RA: reprint author articles (corresponding author articles); R (%): ranking of articles (percentage of all articles published).

(Pant et al. 2012). They show the versatility of using various substrates for sustainable energy production (Pant et al. 2010). Compared with other fuel cells, they can use non-platinum electrodes and hence promise a low cost for the system (Pant et al. 2011). While each fuel cell has its own advantages and relevant applications, the high current density, low temperature of operation and its suitability in automotive applications mark greater importance on PEM fuel cells. It is followed by SOFC, DMFC and MCFC (Kajikawa et al. 2008). The MFC is emerging as a low-cost fuel cell.

The electrode reactions and the components of the fuel cells reveal the importance of key words relating to them such as proton conductivity, oxygen reduction, electro catalyst and methanol oxidation. The distribution of the author keywords and their ranks are presented in Table 6. The research trend over the period of study on 'SOFC', 'PEMFC' and 'DMFC' reveals the equal emphasis on high- and low-temperature fuel cells along with that of the liquid fuel. The tendency of the researchers to optimise the fuel cell components also becomes evident through the keywords,

Table 6. Frequency of author keywords used for bibliometric analysis on fuel cell articles.

Author keywords	TA	92–11 R (%)	92–96 R (%)	97–01 R (%)	02–06 R (%)	07–11 R (%)
Fuel cell	2652	1 (12)	1 (21)	1 (16)	1 (15)	1 (10)
Fuel cells	1523	2 (6.7)	2 (9.5)	2 (8.9)	2 (7.7)	2 (6.1)
SOFC	1134	3 (5.0)	3 (9.2)	3 (7.7)	4 (4.1)	3 (5.0)
SOFC	927	4 (4.1)	6 (4.3)	5 (4.4)	5 (3.9)	4 (4.1)
Hydrogen	782	5 (3.4)	16 (2.0)	16 (2.0)	6 (3.8)	5 (3.5)
SOFCs	717	6 (3.2)	6 (4.3)	6 (4.1)	13 (2.5)	6 (3.3)
DMFC	695	7 (3.1)	N/A	15 (2.1)	3 (4.2)	8 (2.8)
PEMFC	680	8 (3.0)	55 (0.86)	20 (1.7)	7 (3.3)	7 (3.0)
Platinum	603	9 (2.7)	11 (3.2)	10 (2.5)	10 (2.8)	9 (2.6)
PEM fuel cell	563	10 (2.5)	85 (0.57)	49 (0.92)	8 (3.2)	12 (2.4)
Proton conductivity	562	11 (2.5)	192 (0.29)	49 (0.92)	10 (2.8)	11 (2.5)
Cathode	480	12 (2.1)	34 (1.1)	12 (2.4)	18 (1.8)	14 (2.2)
Oxygen reduction	454	13 (2.0)	4 (6.0)	4 (4.5)	17 (1.8)	17 (1.8)
MFC	437	14 (1.9)	N/A	225 (0.25)	84 (0.59)	10 (2.5)
Electrocatalysis	428	15 (1.9)	6 (4.3)	7 (3.2)	20 (1.7)	15 (1.8)
Proton exchange membrane	411	16 (1.8)	55 (0.86)	130 (0.42)	14 (2.3)	18 (1.8)
Methanol	408	17 (1.8)	14 (2.6)	14 (2.2)	9 (2.9)	22 (1.4)
Hydrogen production	408	17 (1.8)	192 (0.29)	37 (1.1)	15 (2.1)	19 (1.8)
Oxygen reduction reaction	402	19 (1.8)	192 (0.29)	130 (0.42)	56 (0.78)	13 (2.2)
Electrocatalyst	391	20 (1.7)	20 (1.7)	25 (1.4)	22 (1.6)	15 (1.8)
Methanol oxidation	382	21 (1.7)	20 (1.7)	57 (0.75)	16 (1.8)	20 (1.7)
DMFC	362	22 (1.6)	N/A	54 (0.83)	12 (2.7)	26 (1.3)
PEMFC	343	23 (1.5)	192 (0.29)	69 (0.67)	28 (1.3)	21 (1.7)
Electrical conductivity	319	24 (1.4)	34 (1.1)	18 (1.9)	20 (1.7)	27 (1.3)
Anode	299	25 (1.3)	20 (1.7)	22 (1.7)	34 (1.1)	24 (1.3)
Modelling	298	26 (1.3)	85 (0.57)	84 (0.58)	24 (1.4)	23 (1.4)
Catalyst	276	27 (1.2)	85 (0.57)	69 (0.67)	32 (1.2)	28 (1.3)
Ionic conductivity	272	28 (1.2)	55 (0.86)	18 (1.9)	30 (1.2)	33 (1.1)
Perovskite	272	28 (1.2)	13 (2.9)	10 (2.5)	43 (1.0)	34 (1.1)
Steam reforming	268	30 (1.2)	27 (1.4)	69 (0.67)	18 (1.8)	41 (1.0)

Note: TA: total published articles in the 20 years; R (%): ranking of articles (percentage of all articles published in the years); N/A: not available.

'proton conductivity', 'proton exchange membrane', etc. The theoretical analysis of the fuel cell publications is increasing as shown by the higher ranking of 'modelling' in the last 4 years.

The distribution of the KeyWords Plus with their rank and percentage in different periods is revealed in Table 7. As a whole, the research trend revealed by KeyWords Plus is consistent with author keywords. The steady upwards movement of 'performance' and 'fuel-cell applications' over every five year interval and their present top positions reveal the current orientation of the research towards high performance of fuel cells, a clear shift from academic interest to applications especially to automotive applications (Barbir 2005). The KeyWords Plus throw light on the important aspect of research such as 'transport' which is increasingly felt as the defining factor in the fuel cell publications. The transport of reactant gases and the product water creates a multiphase equilibrium in the fuel cell. The increasing reference to 'electro catalysts' and 'nanoparticles' emphasises the research trend to arrive at the cost-effective electro catalysts alternative to platinum. Technology forecasting of hydrogen energy and fuel cell by Chen, Chen, and Lee (2010) predicts that the fuel cells would reach a state of maturity shortly and its utilisation depends only on the sustainable production and storage of hydrogen. In this direction, the urge to set out the goal in hydrogen economy is well evident from the recent articles and patents originating from different countries (Klitkou et al. 2007; Mirza 2009; Pilkington et al. 2009). The fuel cell usage in automotive application is expected to play a major role. The adaptation to fuel cell is defined as a chicken–egg problem (Eisenmann and Willis 2004) and the proliferation of fuel cells is highly dependent on achievement cost, publication levels and the investments by the governments. Frost & Sullivan's research (2010) reveals that the fuel cell market is transitioning

Table 7. Frequency of KeyWords Plus used for bibliometric analysis on fuel cell articles.

KeyWords Plus	TA	92–11 R (%)	92–96 R (%)	97–01 R (%)	02–06 R (%)	07–11 R (%)
Performance	4919	1 (17)	18 (3.1)	2 (8.1)	1 (14)	1 (19)
Fuel-cells	3852	2 (13)	1 (15)	1 (14)	2 (13)	2 (13)
Oxidation	2540	3 (8.7)	5 (7.1)	5 (6.0)	3 (9.3)	3 (8.8)
Oxide fuel-cells	2025	4 (7.0)	23 (2.8)	4 (6.2)	5 (6.8)	4 (7.2)
Transport	1848	5 (6.4)	9 (6.0)	8 (5.7)	6 (6.6)	6 (6.3)
Catalysts	1844	6 (6.4)	14 (3.4)	25 (2.7)	7 (5.9)	5 (6.9)
Fuel-cell	1773	7 (6.1)	7 (6.1)	3 (6.5)	11 (5.5)	7 (6.3)
Platinum	1705	8 (5.9)	2 (10)	7 (5.9)	4 (6.8)	11 (5.4)
Electrodes	1656	9 (5.7)	4 (7.2)	9 (5.5)	9 (5.7)	9 (5.7)
Electrooxidation	1515	10 (5.2)	12 (4.9)	12 (4.6)	8 (5.8)	12 (5.1)
Temperature	1483	11 (5.1)	35 (2.2)	17 (3.6)	12 (4.4)	10 (5.6)
Nanoparticles	1352	12 (4.7)	N/A	180 (0.50)	36 (2.3)	8 (5.9)
Oxygen reduction	1262	13 (4.3)	6 (6.4)	10 (5.4)	14 (4.1)	18 (4.3)
Model	1241	14 (4.3)	10 (5.3)	20 (3.2)	13 (4.1)	16 (4.4)
Conductivity	1208	15 (4.2)	15 (3.3)	13 (4.0)	20 (3.7)	17 (4.3)
Electrolyte	1201	16 (4.1)	18 (3.1)	6 (5.9)	18 (3.8)	19 (4.1)
Water	1185	17 (4.1)	22 (3.0)	17 (3.6)	10 (5.6)	20 (3.7)
Cathode	1152	18 (4.0)	114 (0.78)	53 (1.7)	24 (3.3)	13 (4.5)
Fuel-cell applications	1143	19 (3.9)	N/A	898 (0.062)	18 (3.8)	14 (4.4)
Electrocatalysts	1083	20 (3.7)	172 (0.47)	77 (1.3)	28 (2.7)	15 (4.4)
Methanol	1034	21 (3.6)	38 (2.0)	21 (3.1)	16 (3.9)	21 (3.5)
Hydrogen	964	22 (3.3)	29 (2.4)	27 (2.5)	17 (3.8)	24 (3.3)
Reduction	960	23 (3.3)	10 (5.3)	14 (3.9)	30 (2.7)	22 (3.4)
Behaviour	941	24 (3.2)	29 (2.4)	16 (3.6)	27 (2.8)	23 (3.4)
Acid	912	25 (3.1)	15 (3.3)	34 (2.2)	22 (3.6)	27 (3.0)
Kinetics	887	26 (3.1)	3 (7.8)	11 (5.1)	20 (3.7)	39 (2.5)
System	875	27 (3.0)	45 (1.9)	23 (3.1)	32 (2.5)	25 (3.2)
Anode	799	28 (2.8)	114 (0.78)	68 (1.4)	45 (2.0)	26 (3.2)
Membranes	788	29 (2.7)	29 (2.4)	30 (2.4)	15 (4.0)	44 (2.3)
Methane	786	30 (2.7)	38 (2.0)	21 (3.1)	31 (2.6)	32 (2.7)

Note: TA: total published articles in the 20 years; R (%): ranking of articles (percentage of all articles published in the years); N/A: not available.

from validation to the pre-commercialisation stage and Germany, the UK, France and Italy are identified as the opportunity hot spots for the emerging stationary fuel cell technologies.

4. Conclusion

In this study on fuel cell research papers covered by SCI-Expanded, some significant points on the research publication from 1992 to 2011 were observed. There are totally 31,566 articles published in 1313 journals in the 113 Web of Science categories. The main stream research on fuel cell is in automobiles and consumer electronic products. The flagship journal of the field, *Journal of Power Sources* published the most number of articles. It is notable that the USA, contributed the maximum number of independent and internationally collaborative articles while China is racing ahead in this field. By synthetically analysing the distribution and change of author keywords and KeyWords Plus, we described the development of research on fuel cell during the last decade and predict the future direction of fuel cell research. It can be concluded that applications of fuel cell technology to automobile sector and house hold appliances are the orientations of all the fuel cell researches in the twenty-first century.

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